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Optimizing sowing window for wheat cultivation in Bangladesh using CERES-wheat crop simulation model

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ABSTRACT

Sowing date is a crucial factor for wheat (*Triticum estivum* L.) production. From traditional field experiments, optimum sowing date for wheat cultivation could be found out based on existing weather and soil conditions but not possible for futuristic sowing window to address climate change impacts. Crop simulation model can play an important role in this regards. So, a study was conducted at Regional Wheat Research Centre (RWRC), Bangladesh Agricultural Research Institute (BARI), Gazipur, Bangladesh to evaluate the CERES-wheat crop model in simulating optimum sowing window for wheat. Thirteen sowing dates starting from 21 October to 20 December at five days interval were tested with wheat cultivar BARI Gom-26. The model was calibrated and validated with one field experimental data followed by 30 years seasonal runs. Optimum sowing window for wheat is 15 November–30 November in Bangladesh. On an average, grain yield of wheat was reduced by 30–40 kg day^{-1} ha^{-1} when sown from 1 December to 20 December. Similarly, grain yield reduction was about 148–102 kg day^{-1} ha^{-1} with early sown wheat (21 October–14 November).

1. Introduction

Globally, wheat is the most important crop among cereals and covered about 225 million hectares (ha) during 2014–2015 and produced about 737 million tons grain (USDA, 2017). This production scenario is likely to be changed because of increase in Earth's surface temperature along with increasing water demand (Hassanein et al., 2012). Such situations will adversely affect the productivity of wheat in Bangladesh (Jahan et al., 2014). As a second most important cereal crop in Bangladesh, it covered 4.88 lakh ha and produced 13.55 lakh tons grain in 2015–2016 (WRC, 2016). Such area coverage and production might be changed in Bangladesh because of rise in mean temperature by 0.66 °C since 1999 and by 2.13 °C in 2050 (Poulton and Rawson, 2011). Besides, reduced wheat grain yields in Bangladesh are also the cause of inadequate rainfall and high temperature during grain filling stage at the end of growing season (Radmehr et al., 2003). Late seeded wheat crops are mostly exposed to heat stress that accelerate leaf senescence, reduce spikelet density, and cause spikelet abortion and thus results in lower yields (Al-Khatib and Paulsen, 1984; Pfeiffer et al., 2005; Radmehr et al., 2003).

In general, optimum sowing window is determined based on local field experiments that have been done periodically for a limited number of years and locations for a few varieties and final recommendations are extrapolated to other environments. However, the responses of grain yield of wheat to various sowing dates depend on seasonal weather variability across the years as well as locations. Therefore, extrapolating the results of a limited number of environments is not only difficult but may be misleading (Andarzian et al., 2007; Savin et al., 1995; Timsina

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et al., 2008). In this context, crop simulation models that have been evaluated with local experimental data could be valuable tools for extrapolating the experimental results to other years and other locations (Mathews et al., 2002).

Crop simulation models have been used to investigate the performance of different cultivars in a range of sowing dates under different soil and climate scenarios (Bannayan et al., 2013; Bassu et al., 2009; Heng et al., 2007; Pecetti and Hollington, 1997). The DSSAT is a comprehensive decision support system agro-technology tool (Hoogenboom et al., 2010; Tsuji et al., 1998) that includes more than 40 Cropping System Models (Ritchie et al., 1998; Ritchie and Otter, 1985) including CERES-Wheat model. The CERES-Wheat model can be used to simulate the growth and development of dry land and irrigated wheat across a range of latitudes (Hoogenboom et al., 2010; Nain and Kersebaum, 2007). This model has been evaluated and applied in a range of tropical (Timsina et al., 1995), sub-tropical (Heng et al., 2007) and temperate environments of Asia (Timsina and Humphreys, 2006; Zhang et al., 2013). Although CERES-Wheat model is a strong tool for assessing climate change impacts on wheat production, very much limited data are available for executing the program. This is more applicable for newly released wheat varieties in Bangladesh like BARI Gom-26, which covers about 36–40% area in Bangladesh.

Field experiments for finding out optimum sowing window of wheat, like BARI Gom-26, in different locations over the country are laborious as well as expensive. The CERES-Wheat model can easily and effectively handle such difficulties. Therefore, the simulation study was undertaken to find out optimum sowing window for wheat crop in Bangladesh and to find out yield reduction of wheat due to early and late sowing.

2. Materials and methods

2.1. Field study

2.1.1. Site description

The field study was located at Gazipur district in Bangladesh (23.45° N and 90.23° E and 8 m above mean sea level). The study area experiences a sub-tropical monsoon climate.

2.1.2. Soil properties

Experimental soils belongs to Grey Terrace Soil (Aeric Heplaquepts). Nutrient status of experimental soil is shown in Tables 1a & 1b.

2.1.3. Experimentation

One field experiment was conducted in 2013–2014 with six sowing dates and three nitrogen (N) levels. Sowing date was started from 1 November and continued upto 21 December at 10 days interval and N rates used were 40, 80 and 120 kg ha^{-1}. The treatments were laid out in Randomized Completely Block Design (RCBD) with three replications. Four cross ploughing by power tiller was given for land preparation. All stubbles of previous crop T. Aman rice were incorporated into the soil. Phosphorus (P), potassium (K), sulphur (S), zinc (Zn) and boron (B) were used 27, 60, 20, 5 and 1 kg ha^{-1}, respectively. Source of N, P, K, S, Zn and B were urea, triple super phosphate, muriate of potash, gypsum, zinc sulphate and boric acid, respectively. All P, K, S, Zn, B and 2/3rd N were applied during final land preparation and remaining 1/3rd N was top dressed at crown root initiation stage. Seeds were sown at 5 cm depth in continuous in line maintaining line to line distance 20 cm. About 30, 40 and 30 cm irrigation water were applied at crown root initiation, heading and initial grain filling stage. Weeding was done once by hand at 25–30 days after sowing. Fungicide Tilt 250 EC was applied @ 0.5 ml l^{-1} to control Bipolaris Leaf Blight (BpLB) of wheat. Other intercultural operations were done as and when necessary. Wheat crops of different plots were harvested at fully matured stage. Grain moisture was adjusted at 12% after sun drying of harvested grain. Grain yield and yield contributing characters were recorded and used for validation of DSSAT model.

Table 1a
Physical properties of Gazipur soil.

Soil layer (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (Mg m^{-3})
0–15	30.84	46.42	22.74	1.52
15–30	20.84	47.35	31.81	1.53
30–60	20.48	40.24	39.28	1.56
60–90	23.48	43.71	32.81	1.57
90–120	19.84	42.35	37.81	1.61
120–150	18.84	45.21	35.95	1.63
150–180	19.36	46.28	34.36	1.66

2.2. Simulation study

The simulation study was conducted for Gazipur location using DSSAT v.4.6 model. The model was run using the weather and soil data of Gazipur. The soils of the study site were characterized as silty clay loam with moderate drainage.

2.2.1. Weather data

Generally warm and humid climate prevails at Gazipur. Weather data of Gazipur during wheat growing season are shown in Table 2.

2.2.2. Model description

DSSAT v.4.6 model (CERES-Wheat Crop Simulation Model) was used for the study. The model was run with six data sets: soil, weather, genetic coefficient, experimental file (X file), annual file (harvested data) (A file) and seasonal (time series data on leaf area index, dry matter partitioning data, etc) files (T file). Soil data included soil characteristics such as site latitude and longitude, soil type and soil series, pH, bulk density, soil texture and soil nutrient status like N and C content. Weather file included temperature (both maximum and minimum), humidity, solar radiation, rainfall etc. DSSAT model required some of crop management data like cultivar, sowing/planting date, line sowing/broadcast, plant spacing, nitrogen levels, tillage practices and organic amendments (Jones et al., 2003) in experimental file (X file) to simulate crop productivity. Phenological data like different stages of crop growth such as days to heading, days to anthesis (flowering), days to physiological maturity, days to harvest, yield contributing parameters, grain yield and biological yield were also recorded. In order to simulate yields under different sowing dates, the CERES-Wheat model was calibrated and validated initially. Climatic data were collected from the weather station of Gazipur under the Department of Metrology, Peoples Republic of Bangladesh. The input files, such as weather file, soil file, A file, T file (leaf area index, dry matter partitioning data, etc) were prepared for applying in the CERES-Wheat model to predict wheat yields under different sowing dates.

2.2.3. Optimum window for sowing dates of wheat

Optimum window for sowing dates of wheat was based on genetic co-efficient of wheat cultivar BARI Gom-26, soil file, weather file and seasonal file. One experiment was simulated having 13 sowing dates starting from 21 October to 20 December at 5 days intervals on BARI Gom-26 to find out optimum sowing window for wheat cultivation in Bangladesh.

2.2.4. Model application

DSSAT v.4.6 model (CERES-Wheat Crop Simulation Model) was run (seasonal run) for 30 years from 1980 to 2010. Predicted wheat yields were generated using this seasonal run. Scenarios (30 years data) were developed to assess the sensitivity of the crop to different sowing dates for adjusting/minimizing the grain yield reduction of wheat for Bangladesh. These scenarios were implemented in the DSSAT model, and the outputs were analysed using graphical techniques to compare

Table 1b
Chemical properties of Gazipur soil.

Soil layer (cm)	pH	Organic carbon (%)	Total N (%)	NO_3^- N (mg kg^{-1})	NH_4^+ N (mg kg^{-1})	Available phosphorous (mg kg^{-1})	Available potassium (meq 100 g^{-1})
0–15	6.1	1.04	0.11	11.4	1.8	9.06	0.29
15–30	6.2	0.93	0.09	9.8	2.0	8.78	0.27
30–60	6.2	0.77	0.08	7.6	2.2	7.11	0.24
60–90	6.3	0.52	0.06	6.4	2.4	5.63	0.22
90–120	6.4	0.46	0.05	5.3	2.6	5.09	0.18
120–150	6.5	0.41	0.04	4.9	2.8	3.89	0.15
150–180	6.7	0.36	0.03	4.1	2.9	3.21	0.14

Table 2
Weather data of Gazipur (35 years mean).

	Average Temperature (°C)		Total rainfall (mm)	Average sunshine hour
	Maximum	Minimum		
October	31.9	23.7	173.1	6.98
November	29.6	18.4	28.9	7.70
December	26.1	13.7	8.5	6.90
January	24.8	12.1	6.6	6.94
February	28.1	14.9	19.3	7.82
March	31.9	19.4	46.0	8.20
April	33.6	22.9	127.9	7.92

climate change effect.

3. Results and discussion

3.1. Calibration and validation of CERES-Wheat model

With the help of several wheat trials (regarding dates of sowing, irrigation and N rates etc), the genetic coefficient was computed by the use of tool GLUE of DSSAT (Table 3).

The P1 V is optimum vernalizing temperature, required for vernalization expressed in days, P1D indicates photoperiod response (% reduction in rate/10 h drop in pp), P5 is grain filling (excluding lag) phase duration (°C-d). G1, G2 and G3 means kernel number per unit canopy weight at anthesis (# g^{-1}), standard kernel size for wheat grown under optimum conditions (mg) and standard, non-stressed mature tiller weight (including grain) (g dwt); respectively. PHINT indicates interval between successive leaf tip appearances expressed in °C-d.

The performance of the CERES-Wheat model was evaluated through comparison of simulated verses observed yield (Fig. 1). The trend line was almost close with the 1:1 line, indicating that the model was performing well for simulating the yield of wheat grown in Bangladesh environment. The trend line showed satisfactory predictability, as seen through very high R^2 value. The percent error of estimate lied within the range of −10.9% to 5.3%, indicating that the model could be taken to application platform for finding out optimum sowing window for wheat production.

3.2. Effect of different sowing dates on leaf area index

Effects of different sowing dates on maximum leaf area index (LAI-max) of wheat at Gazipur site are shown in Fig. 2. The LAI-max of early sown wheat ranged from 3.31 to 3.80 for 21 October to 10 November seeding. The LAI-max was the highest (3.95–4.11) with 15 November to 30 November sown wheat crop. The LAI-max started to decline from 5 December to 20 December seeding in which the range was 3.50–2.43. The LAI is generally increased over growing time and it is the highest at maximum tillering stage and almost static upto anthesis (flowering) and then in decreasing trend upto maturity (Bai et al., 2005; Wu et al., 2013). The LAI-max was relatively higher at the middle of sowing dates resulting in higher grain yield of wheat. This result corroborates with the findings of Pourreza et al. (2009) who reported that grain and biomass yields of wheat largely depends on LAI. Early sown wheat was exposed to early heat stress during crop growth period resulting in less LAI-max. Similarly late sown wheat was exposed to late heat stress during grain filling period.

Table 3
Genetic coefficient of wheat.

Cultivar	P1V	P1D	P5	G1	G2	G3	PHINT
BARI Gom-26	0	92	730	23	46	3.8	70

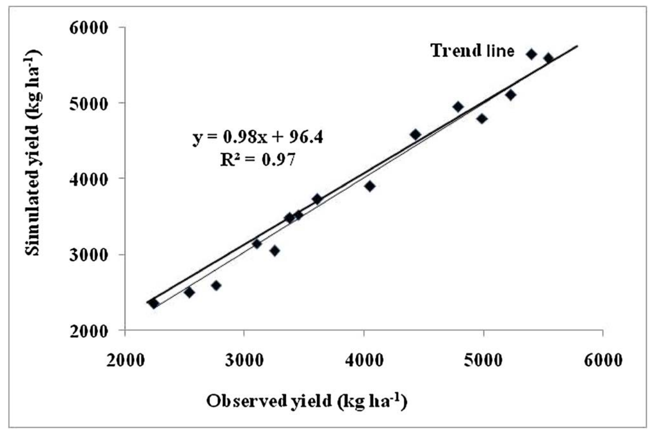


Fig. 1. Performance evaluation of CERES-Wheat model through comparison of observed grain yield verses simulated grain yield.

3.3. Effect of sowing dates on days to maturity

Days to maturity of wheat depends on date of sowing (Fig. 3). Days to maturity were 102 for wheat sown on 21 October, and increased upto 113 days when sown on 10 November. The maturity duration was 114–115 days upto 5 December seeding and then decreased to 112–106 days. The lowest maturity duration was recorded with 20 December sown wheat. Either early or late sown conditions induced short growth duration of wheat crop might be because of heat stress (relatively higher temperature prevailed than optimum temperature) that resulted in shorter total crop duration. Similar findings were also reported by Haris et al. (2013) who found that higher temperature during growing period of wheat decreased crop growth duration and ultimately lower grain yield of wheat. It was also reported that simulated days to maturity of wheat sown in 15 December was 10 days shorter than that of sown in 15 November (Haris et al., 2013).

3.4. Effect of sowing dates on grain yield

Effect of different sowing dates on grain yield of wheat is presented in Fig. 4. Grain yield of wheat was very much responsive to sowing dates that followed quadratic behaviour showing reduced grain yields

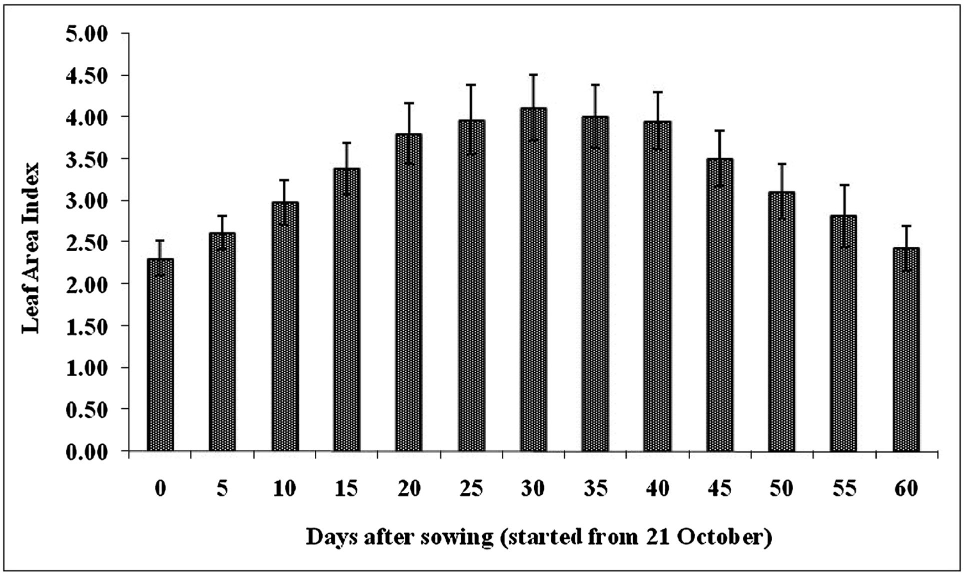


Fig. 2. Leaf area index (max) of wheat as influenced by different sowing dates.

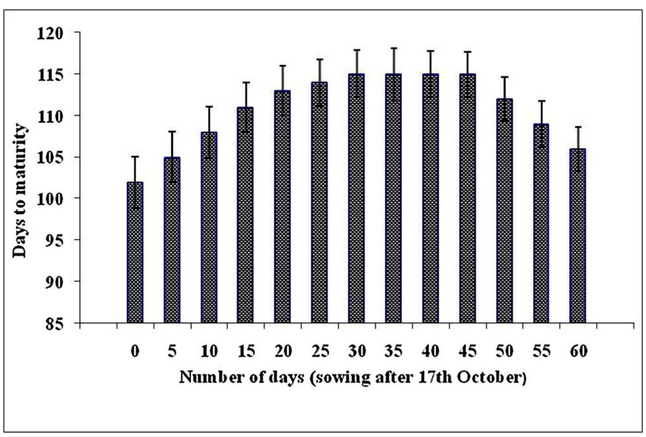


Fig. 3. Days to maturity of wheat as influenced by different sowing dates.

in either early or late sowing conditions than optimum time of seeding. Grain yield in wheat varied from 2651 kg ha^{-1} to 4401 kg ha^{-1} for 21 October to 10 November sowing might be due to early heat stress (i.e. relatively higher temperature) which induced early maturity than optimum sowing dates. Similar findings were also reported by Rezzoug and Gabriella (2009) where growth of wheat seedlings was affected by relatively high air temperature with early sown crop. Source and sink relationship with early sown wheat was hampered resulting reduced grain yield than optimum condition (Jahan et al., 2014). Similar findings were also reported by Heng et al. (2007) who obtained higher grain yield of wheat with late November seeded crop compared to early October seeding in western Asia.

Wheat yield was relatively higher (ranged from 4680 kg ha^{-1} to 4825 kg ha^{-1}) from 15 November to 30 November sowing indicating that optimum sowing window for wheat cultivar BARI Gom-26 is 15 November (4680 kg ha^{-1}) to 30 November (4786 kg ha^{-1}). The highest grain yield (4825 kg ha^{-1}) was recorded from 25 November seeding. Prevailing air temperature might have played an important role to maximize wheat yield. So, balance in source and sink relationship under optimum growth duration of a crop create favourable conditions for photosynthate distribution resulting in higher grain yield. These results are corroborated with the findings of Fayed et al. (2015) who obtained the highest grain yield in 15 November sown wheat crop compared to 15 October seeded one. Mediate sowing date (mid-

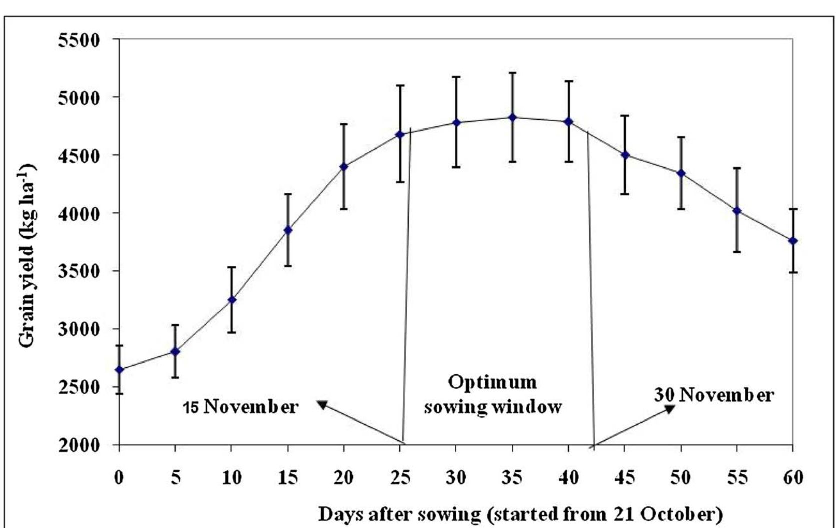
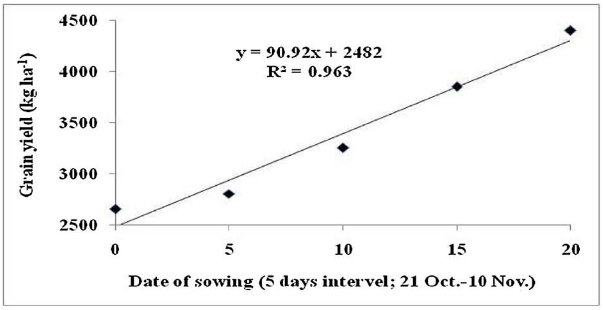
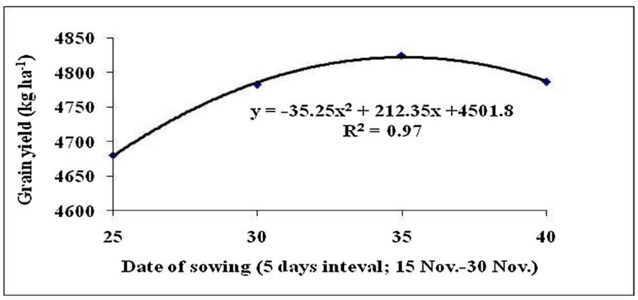


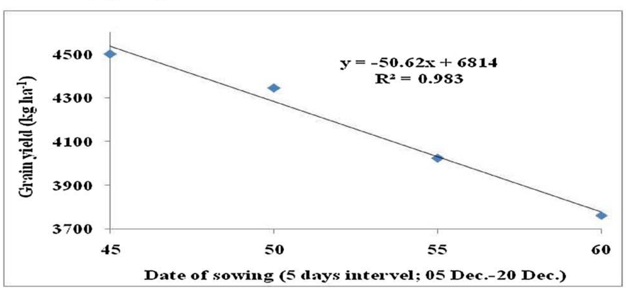
Fig. 4. Effect of sowing date of wheat on grain yield of wheat.



a) **grain yield of wheat and early date of sowing**



b) **grain yield of wheat and mediate date of sowing**



c) **grain yield of wheat and late date of sowing**

Fig. 5. Relationship between grain yield of wheat and early, mediate and late date of sowing.

November) favoured vegetative growth and development of spring wheat cultivars to produce significantly the highest biological yield. Decreasing trend of wheat yields from 5 December to 20 December seeding in which yield rang 4499 kg ha^{-1} to 3762 kg ha^{-1} has been found. High temperature stress was mostly responsible for such lower grain yields. High temperature during grain filling period slows the rate of grain filling and accelerates senescence due to decrease in photosynthetic activities per unit leaf area (Al-Khatib and Paulsen, 1984; Zhao et al., 2007). Similar findings were also reported by Balwinder-Singh et al. (2016). Simulated grain yield of wheat in central Punjab, India increased with shifting in sowing dates from 10 October to 20 November (mean of 2.9 t ha^{-1}), and decreased thereafter. Lower grain yield of early sown wheat was associated with a shorter vegetative growth period and relatively lower grains number spike^{-1}, smaller grain size and reduced grain weight, while on the other hand, late sown wheat yields are associated with both shorter vegetative phase and reproductive periods (Arora and Gajri, 1998).

Relationship between grain yields of wheat with early (21 October–10 November), mediate (15 November–30 November) and late sown (5 December–20 December) crops are shown in Fig. 5a, b & c. It was observed that there was a positive liner relationship between grain yield of wheat and early date of sowing, while it was negative liner relationship with late sowing date. In case of mediate sown wheat, polynomial relationship was observed. Negative correlation between grain yield and sowing date were reported for late sown wheat (Fayed et al., 2015). Gain in wheat yield was about 91 kg ha^{-1} for every day delayed sowing started from 21 October to onwards upto 10 November. Since early sown crops were exposed to higher temperature compared to optimum sowing time, congenial growing conditions favoured higher grain yield upto 10 November seeding. In mediate sown crop, gain in wheat yield was about 7 kg ha^{-1} for every day late/delay sowing starting from 15 November to onwards upto 30 November. Prevailing air temperature was favourable for such yield gain. Similar results were also reported by Jahan et al. (2014). In case of late sown wheat, about 51 kg ha^{-1} day^{-1} grain yield was reduced for every day late/delay sowing starting from 5 December to 20 December. Comparatively higher air temperature was responsible for such yield reduction. Increased temperature in reproductive phase of wheat reduces spikelet density, and cause spikelet abortion, resulting in lower grain yield (Pfeiffer et al., 2005). Balwinder-Singh et al. (2016) also reported yield reduction by 52 kg ha^{-1} day^{-1} (0.8% day^{-1}) with delay in sowing from 10 November to 30 December in central Punjab, India.

3.5. Optimum sowing window for wheat

The highest grain yield of 4825 kg ha^{-1} was recorded from 25 November sowing. In Bangladesh, annual yield variability because of wheat sowing time is around 5% of long term yield records (Jahan et al., 2014). This implies that the sowing dates that yielded 95% of the highest grain yield or more lies is the optimum sowing window. Accordingly, 25–40 days after 21 October that is 15 November to 30 November is the optimum sowing windows for wheat cultivation in Bangladesh. The length of optimum sowing window is 15 days. At this sowing window grain yield of wheat ranged from 4680 kg ha^{-1} to 4825 kg ha^{-1}. Similar findings were reported by Andarzian et al. (2007) and they reported a wider window of 30 days (5 November–5 December) for profitable wheat cultivation in Iran. Similarly, Balwinder-Singh et al. (2016) found 20 November as the pick point of optimum sowing window for wheat in central Punjab using APSIM model.

3.6. Effect of sowing dates on above ground biomass yield

Biomass yield responses to sowing dates of wheat are shown in Fig. 6. In early (21 October to 10 November sowing) sown wheat, biomass yield ranged from 4575 kg ha^{-1} to 8158 kg ha^{-1}. High temperature stress in early sown crop was responsible for reduced growth duration and less accumulation of photosynthate. As a result, less biomass yield was produced. This result corroborates the findings of Andarzian et al. (2007) who obtained lower biomass yield in early sown wheat in Khuzestan, Iran. After 10 November, biomass yield of wheat

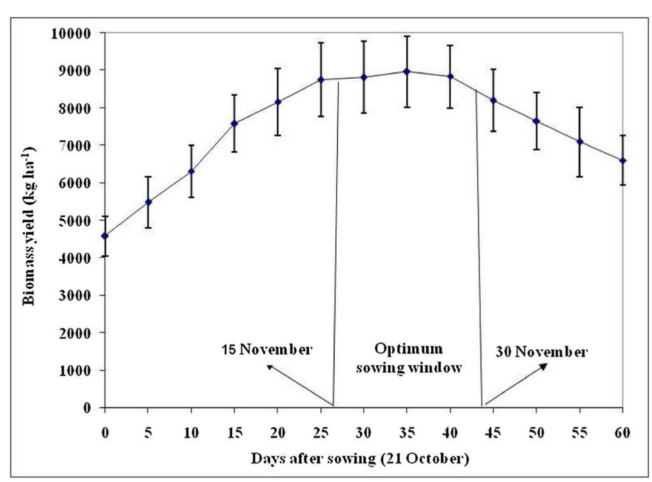


Fig. 6. Effect of sowing date of wheat on biomass yield of wheat.

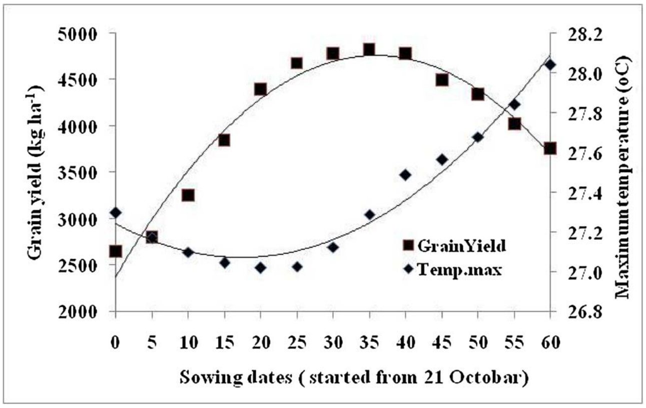


Fig. 7. Relationship between grain yield of wheat and maximum temperature at different sowing dates.

increased gradually upto 25 November (8745 kg ha^{-1}), which was almost static upto 30 November and then decreased sharply. Crop growth duration of wheat sown in this period was comparatively higher resulting in higher biomass yield (Jahan et al., 2014). Thereafter biomass yield started declining ranging from 8190 kg ha^{-1} (in 5 December sown wheat) to 6598 kg ha^{-1} (in 20 December sown wheat). Biomass yield of wheat sown in this period was lower due to late and terminal heat stresses.

3.7. Effect of ambient temperature on grain yield

The relationship between average maximum and minimum temperatures (35 years mean) with grain yields of wheat are shown in Figs. 7 and 8, respectively. In the earliest sown wheat (21th October), average maximum temperature was 27.3 °C and it was declining with the advancement of sowing dates upto 10 November (27.0 °C). As the temperature was decreasing, grain yield increased from 2651 kg ha^{-1} to 4401 kg ha^{-1}. However, the maximum temperature was 27.0 °C on 15 November that increased upto 27.3 °C on 30 November and grain yield ranged from 4680 to 4825 kg ha^{-1}. BARI Gom- 26 cultivar is some extent heat tolerent (WRC, 2016) and thus can compensate some yield loss. After 30 November, grain yield sharply declining over the advancement of sowining time upto 20 December related with increased maximum temperature from 27.6 to 28.0 °C.

Grain yield of wheat was 2651 kg ha^{-1} when average minimum temperature was 15.2 °C in 21 October sown crop that jumped to 4401 kg ha^{-1} in 10 November seeding because of reduction in minimum temperature (Fig. 8). Minimum temperature was the lowest (14.3 °C) on 15 November and 20 November seeding and then started to

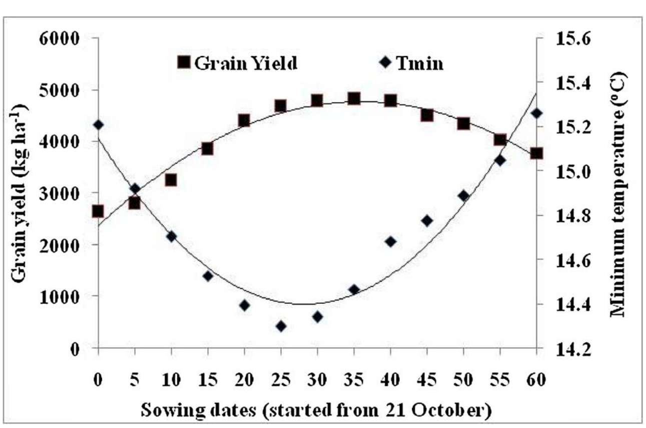


Fig. 8. Relationship between grain yield of wheat and minimum temperature at different sowing dates.

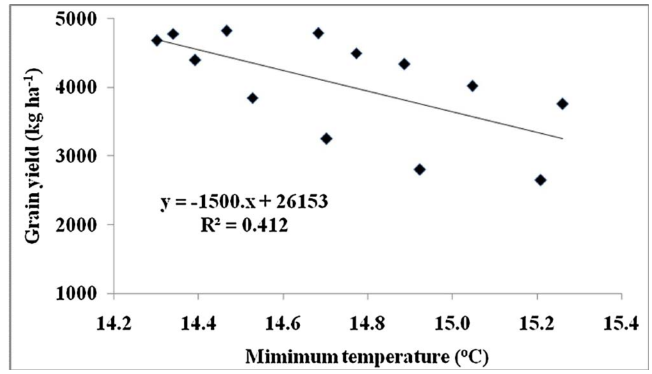


Fig. 9. Effect of minimum temperature on grain yield of wheat.

increase upto 20 December. Grain yields were 4680 to 4825 kg ha^{-1} in 25 November and 30 November seeding because of prevailing minimum temperature was ~15 °C at the time of grain filling period. After 30 November, grain yield started to decline sharply (from 4499 to 3762 kg ha^{-1}) with the advancement of sowing dates upto 20 December which might be due to increased minimum temperature from 14.8 to 15.3 °C resulting shorter grain filling period.

Grain yield of wheat was negatively related with increased minimum temperature (Fig. 9). The functional relationship suggested that 41% ($R^2 = 0.412$; $p \leq .05$) of variation in grain yield of wheat could be explained from the variation in minimum temperatures. Wheat grain yield decreased by about 1500 kg ha^{-1} season^{-1} for 1 °C rise in minimum temperature compared to optimum temperature during the cropping cycle.

3.8. Relationship of grain yield of wheat with days to maturity

A positive liner relationship between grain yield of wheat and days to maturity was observed (Fig. 10). The functional relationship suggested that 90% ($R^2 = 0.901$; $p \leq .01$) of the variations in grain yields of wheat could be explained from the variations in days to maturity. Grain yield of wheat is highly depends on total grain filling period. If this period longer, source and sink relationship would be effective for grain filling which enhanced total grain yield as well as total productivity (Jahan et al., 2014). About 162 kg wheat grain yield day^{-1} ha^{-1} increased for one day increase in days to maturity.

4. Conclusion

Wheat is one of the most thermo-sensitive crops. As winter season of Bangladesh is very short, its yield mostly depends on sowing time along with prevailing optimum temperature during grain filling period. In early sown wheat (21 October–10 November), germination, seedling

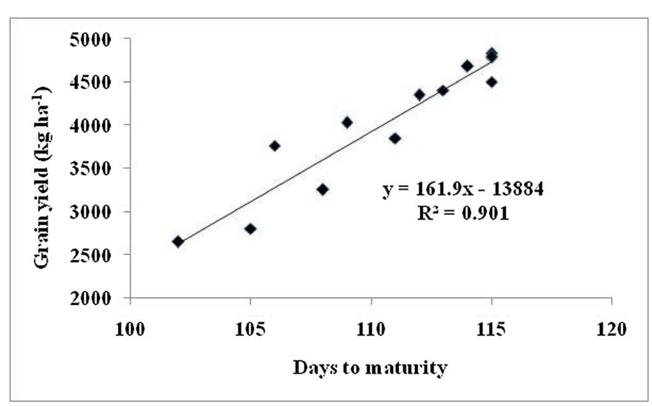


Fig. 10. Relationship between grain yield and days to maturity of wheat.

emergence, crown root initiation and vegetative stage, tillering, booting, heading, anthesis (floweing), grain filling and maturity stages were affected by early heat stress resulting in reduced grain yield by 2.89% per day for every one day early sowing of wheat. Similar senario was observed for late sown (5 December–20 December) wheat crop. Grain yield of wheat also reduced on an average 1.28% per day for every one day delay sowing of wheat due to late heat stress effects. Optimum sowing window (15 November–30 November) enhenced grain yield of wheat might be due to prevailing optimum temperature of 15 °C–25 °C for night and day times, respectively having 114–115 days optimum maturity duration. Finaly it may be concluded that optimum sowing window for wheat cultivation in Bangladesh is from 15 November to 30 November.

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